The following article appeared in Appl. Phys. Lett. 64, 1386 (1994) and may be found at http://dx.doi.org/10.1063/1.111915

2000 V 6H-SiC *p-n* junction diodes grown by chemical vapor deposition

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(Received 30 August 1993; accepted for publication 10 December 1993)

In this letter we report on the fabrication and initial electrical characterization of the first silicon carbide diodes to demonstrate rectification to reverse voltages in excess of 2000 V at room temperature. The mesa structured 6H-SiC p^+n junction diodes were fabricated in 6H-SiC epilayers grown by atmospheric pressure chemical vapor deposition on commercially available 6H-SiC wafers. The devices were characterized while immersed in Fluorinert™ to prevent arcing which occurs when air breaks down under high electric fields. The simple nonoptimized diodes, whose device areas ranged from 7×10^{-6} to 4×10^{-4} cm^2, exhibited a 2000 V functional device yield in excess of 50%.

The inherent material properties of the 6H polytype of single-crystal silicon carbide are very attractive for use in power semiconductor electronics.[1,2] A recent theoretical appraisal conducted by Bhatnagar and Baliga[3] indicates that 6H-SiC power metal-oxide-semiconductor field-effect transistors (MOSFETs) and Schottky diode rectifiers could operate over higher voltage and temperature ranges, have superior switching characteristics, and yet have die sizes nearly 20 times smaller than correspondingly rated silicon-based devices. These improved device characteristics arise from the inherent material property advantages that 6H-SiC enjoys over silicon, namely a higher breakdown field (> 5 times that of Si) that permits much smaller drift regions (i.e., much lower drift region resistances), a higher thermal conductivity (> 3 times that of Si) that enables superior heat dissipation, and a wide band-gap energy (2.9 eV) that permits higher junction operating temperatures.

Due to the fact that reproducible silicon carbide wafers and epilayers were unavailable before 1989, silicon carbide device fabrication technology is relatively immature compared to silicon power device fabrication technology. Several important SiC device fabrication and crystal growth issues must be resolved and optimized before the theoretical advantages of silicon carbide can be realized in highly useful SiC power devices.[2,4] One crucial issue is the need for continued improvement in epitaxial growth of high-quality silicon carbide epilayers, where control of both the uniformity and the background doping concentrations of SiC epilayers will have to be improved if practical multikilovolt SiC devices are going to be realized. Prior to this work, the highest blocking voltage ever reported in a silicon carbide semiconductor diode was 1400 V.[5] This letter reports on the fabrication and initial electrical characterization of the first silicon carbide diodes to demonstrate rectification to reverse voltages in excess of 2000 V at room temperature.

The 6H-SiC epilayer structure shown in Fig. 1 was grown on a substrate cut from a commercially available[6] n^+ 6H silicon-face SiC substrate polished 3° to 4° off the (0001) SiC basal plane. The atmospheric pressure chemical vapor deposition (CVD) system, gases, and general growth procedures used are described elsewhere.[7,8] The key lightly doped blocking voltage layer was grown using one aspect of the improved dopant control process called "site competition epitaxy."[9] By growing at a silicon to carbon atomic ratio of 0.1, most of the nitrogen present in the CVD system (whether it is a residual contaminant or intentionally introduced) is excluded from incorporating into the growing SiC crystal for the reason that the excess carbon species "outcompetes" the nitrogen species for the carbon lattice site that nitrogen normally occupies when it dopes SiC. For the 1450 °C atmospheric pressure growth of the *n* blocking voltage layer, we intentionally introduced 118 at. ppm nitrogen into the reactor (which is more than half of the 200 at. ppm silicon present in the system) and yet achieved an apparent net dopant concentration of $2–5\times10^{15}$ cm^{-3}, one of the purest 6H-SiC epilayers reported to date.

A 2000 Å thick aluminum etch mask defining circular and square diode mesas, ranging in area from 7×10^{-6} cm^2 to 4×10^{-4} cm^2, was applied and patterned by liftoff. The diode mesas were etched to a depth of approximately 6 μm using reactive ion etching (RIE) in 80% SF_6: 20% O_2 under 300 W rf at a chamber pressure of 250 mTorr. The process was

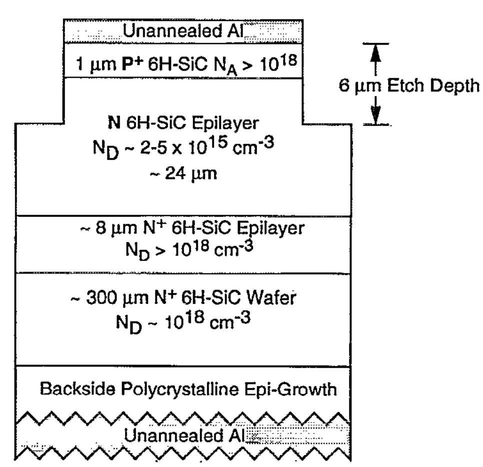

FIG. 1. 6H-SiC *p-n* junction diode cross section. No explicit junction termination geometries or sidewall dielectric passivations were employed.

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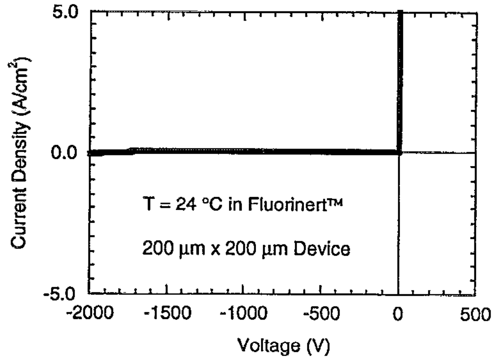

FIG. 2. 6H-SiC p-n junction current-voltage characteristics on a linear scale at room temperature. The device is immersed in clean Fluorinert™ (a high dielectric strength insulating fluid) to prevent the high-voltage arcing which occurs in air. The 2000 V blocking voltage shown is the highest silicon carbide diode blocking voltage ever reported.

self-aligned in that the aluminum etch mask also served as the top contact to the p^+ layer in the finished devices. Unpatterned electron beam evaporation of aluminum onto the back side of the wafer completed the fabrication process, resulting in devices with the cross-section displayed in Fig. 1. No contact anneals were performed in this work for the simple reason that the measurement of fundamental rectification properties could be accomplished without minimizing contact resistances.

All electrical measurements were carried out in the dark on a probing station using computer controlled current-voltage (I-V) and capacitance-voltage (C-V) instrumentation. I-V characteristics above and below -1100 V were measured with different instruments due to measurement equipment resolution and operating voltage limitations. The apparent carrier concentration of the lightly doped n-type blocking voltage layer, as measured at room temperature on the largest area diodes by 100 kHz and 1 MHz C-V techniques, was within the range of $2–5\times10^{15}$ cm^{-3}. When probed in air, the diodes exhibited excellent rectifying characteristics as long as reverse-bias voltages were held below 300 to 400 V. The application of larger reverse voltages resulted in destructive electric arcs emanating from the device mesa periphery. Based on previous experience that the air around the device was associated with the failure,[10] the diode wafer was immersed in a shallow tub filled with Fluorinert™ FC-77[11] (a high dielectric strength insulating fluid) for all of the high-voltage testing beyond 300 V reverse bias.

When immersed in clean Fluorinert™, the devices exhibited room-temperature rectification to reverse voltages in excess of 2000 V as shown in Fig. 2. Over half of the dozen diodes tested in fresh Fluorinert demonstrated 2000 V blocking voltages, and the maximum rectifying voltage observed was 2200 V. This represents the highest blocking voltage ever reported in a silicon carbide diode, surpassing the largest previously reported silicon carbide diode rectifying voltage by over 600 V.[5] The reverse I-V of Fig. 3 is typical, but leakage current variations by as much as an order of magnitude above and below the Fig. 3 characteristic were measured.

In clean Fluorinert™, the diodes failed catastrophically between 2000 and 2200 V reverse bias, but the exact mechanism for this failure is unclear at this time. No evidence of avalanche breakdown was observed in any I-V measurements. Despite attempts to limit excessive current flow during testing, the high-voltage reverse failure events were so catastrophic that the device mesas were destroyed as shown in Fig. 4. The arcing residues at the crater sites left behind by device annihilations appear to suggest that failure is occurring along the mesa periphery, possibly due to dielectric failure of the Fluorinert™ under excessively high electric fields. A supporting observation as to the role of the Fluorinert™ in device failure was that the highest blocking voltages were only obtainable in solutions of fresh, clean Fluorinert™. The measured catastrophic failure voltages of diodes on the wafer declined when a given tub of Fluorinert™ degraded after the destructive testing of a few diodes, presumably a result of chemical breakdown or the presence of particulate debris

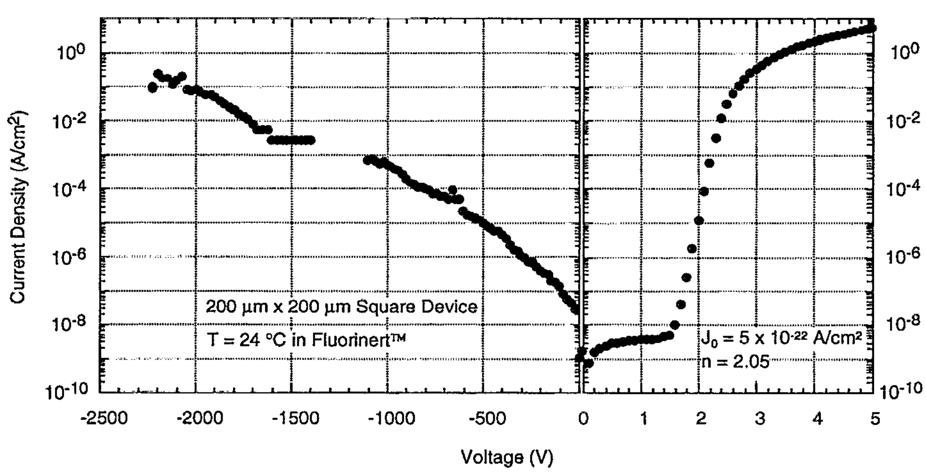

FIG. 3. 6H-SiC p-n junction current-voltage characteristics on a semilogarithmic scale at room temperature. The reverse characteristics above and below -1100 V were measured with different instruments due to measurement equipment resolution and operating voltage limitations.

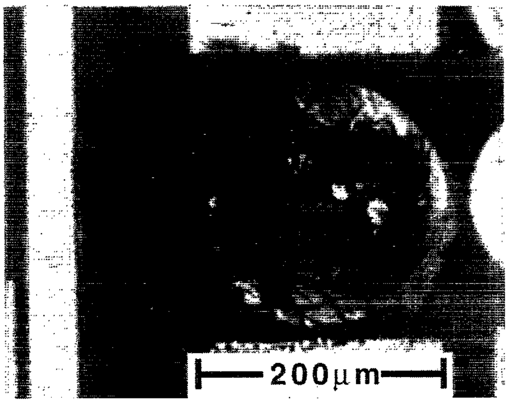

FIG. 4. A 6H-SiC diode following catastrophic failure at over 2000 V reverse bias. The failure has exploded away the device mesa leaving behind a crater and arc residue patterns.

generated by the catastrophic failures. Maximum high-voltage performance on nondamaged devices was restored only when the tub and wafer were solvent cleaned and dried and the sample reimmersed in fresh Fluorinert™.

The forward characteristics of the diodes were very well behaved, exhibiting saturation current densities below 10^{-20} A/cm^2 and consistent ideality (n) factors very close to 2. Typical forward characteristics for the largest area devices are shown in Fig. 3. The series resistance demonstrated by the nonexponential behavior above 2.5 V forward bias is around 0.3 $\Omega\,cm^2$. This specific on resistance is roughly an order of magnitude larger than the specific on resistance theoretically calculated for the lightly doped 24 μm thick drift region, but this is likely due to parasitic series resistance arising from nonoptimized unannealed ohmic contacts and the presence of back side polycrystalline SiC material deposited on the bottom of the wafer during the epitaxial growth.

Even though avalanche breakdown was not observed in the diodes, it is nevertheless useful to estimate the peak electric field in the devices. First-order single-sided p^+n junction calculations indicate that the junction depletion might extend through the entire 24 μm thick n-layer at 2200 V reverse bias,[12] so the possibility of depletion layer reach-through to the buried n^+ epilayer was accounted for in the calculations.[13] Peak junction electric field values of 1.4–1.8 MV/cm were calculated for the 2–5×10^{15} cm^{-3} measured doping range. These values fall just below the low-doped junction breakdown fields predicted by extrapolation of measured breakdown data from more highly doped ($\sim10^{16}$–10^{19} cm^{-3}) junctions.[5]

In summary, we have produced the first silicon carbide diodes to achieve rectification to reverse voltages in excess of 2000 V, representing a 600 V improvement in reported silicon carbide diode blocking voltage capability. A functional yield of over 50% was obtained on these small-area prototype diodes, but it is important to note that micropipes and possibly other defects documented in 6H-SiC wafers and epilayers will likely cause difficulties as device areas are enlarged.[4,14,15] The reduction of such defects and the continued improvement of SiC epitaxial growth, ohmic contact, and dielectric passivation technologies will be crucial areas of continued research towards the realization of highly advantageous silicon carbide power devices.

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